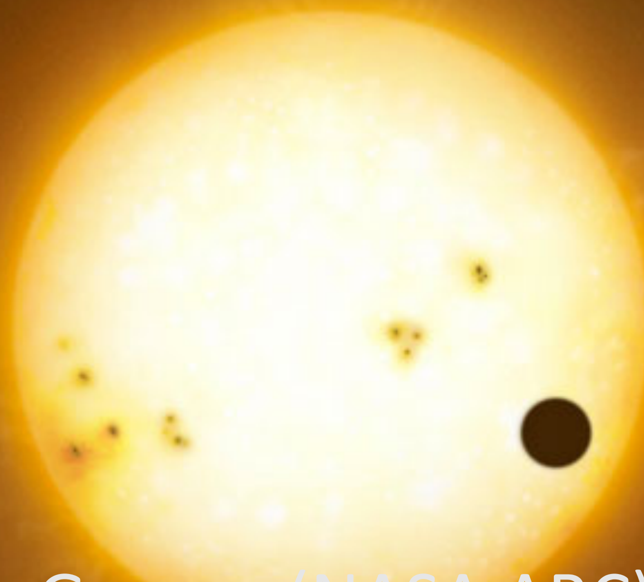
Characterizing transiting planets with JWST spectra: Simulations and Retrievals



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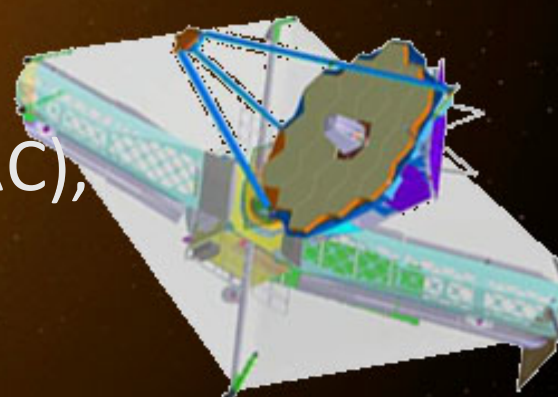
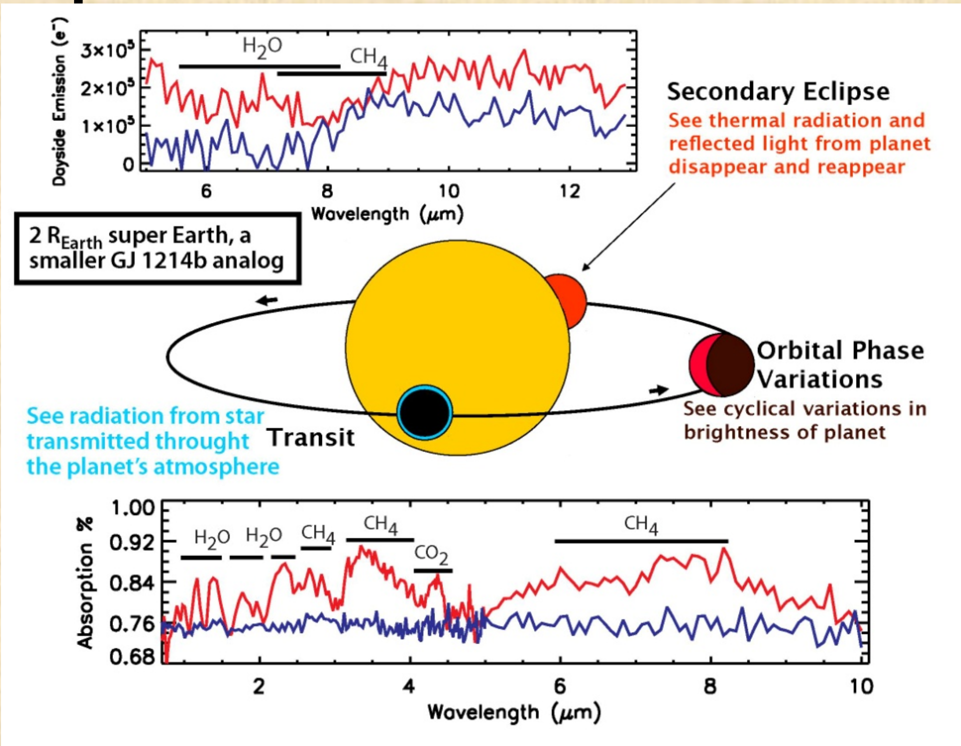
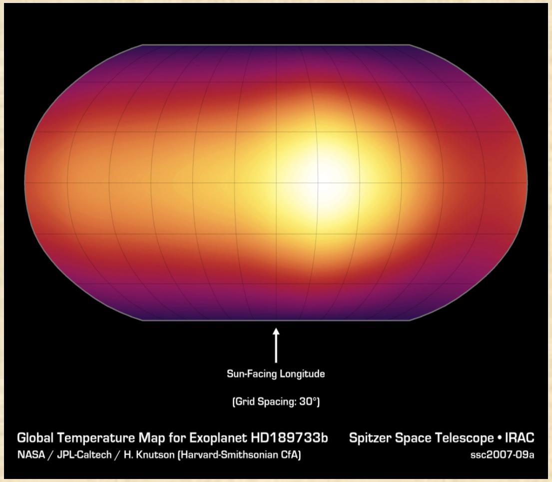


Planet transit / eclipse observations

- Spectra provide best diagnosis of atmospheres:
  - Compositions: inventory of molecules requires large spectral range
  - Transmission spectra best for abundances: insensitive to T profile but only sample high atmosphere
  - Emission spectra sample more atmosphere and reveal temperature profiles with retrievals



- Photometry useful for
  - Phase curves to study response to insolation and energy transport
  - Confirming transits , e.g. small TESS objects, Kepler Earth in GV HZ
  - Eclipse mapping: temperature variations across planet disk



Some progress from transit spectroscopy

- Molecules & atoms identified in exoplanet atmospheres
  - H2O, CO (CH4, CO2), Na, other alkali, HI, CII, OI,…
- Measured temperature-pressure profiles from hot Jupiter emission spectra
  - e.g., HD 189733b (e.g., Line+ 2014), WASP-43b (Kreidberg+ / Stevenson+ 2015)
- Some Neptune-sized planets have been diagnosed
  - HAT-P-11 (Fraine+ 2014) and GJ 436b (Knutson+, etc.)
- Sub-Neptunes and super-Earths have been difficult
  - GJ 1214b: flat absorption, no sec. eclipse (many people…)
  - Promise of cooler planets like K2-3 system (Crossfield+ 2015): might be cool enough to not have clouds

Questions about exoplanet atmospheres

- *What are their compositions?*
  - Elemental abundances:
    - C/O and [Fe/H]: Both are formation diagnostics
  - Chemical processes
    - Identify equilibrium chemistry
    - Identify disequilibrium chemistry:
      - Vertical mixing, photochemistry, ion chemistry…
    - 3-D effects: spatial variations
- *Energy Budget and Transport*
  - 1-D structure: measure profiles, inversions present?
  - Dynamical transport: day/night differences
- *Clouds*
  - Cloud composition, particle sizes, vertical & spatial distribution
  - Removing cloud effects to determine bulk properties
- *Anything about low mass / small (< ~2R_e) planet atmospheres*
- *Trends with bulk parameters (mass, insolation, host stars, …)*
  - Requires a population of diverse planets

New JWST Transiting Planet Assessment

Model some known planet types, assess information in simulated JWST spectra

- Select archetypal planets from known system parameters
  - Hot Jupiter, warm Neptune, warm sub-Neptune, cool super-Earth
- Create model transmission and emission spectra (M. Line)
- Simulate JWST spectra using performance models (TG)
  - Simulate slitless modes with large bandpasses & good bright limits: NIRISS SOSS, NIRCam grisms, MIRI LRS slitless 1 – 11 μm
  - My code is based on validated instrument models, detector parameters, JWST background models, random & systematic noise
- Perform atmospheric retrievals (M. Line) to assess uncertainties in abundances, T-P profiles
  - Focus on uncertainties, not absolute parameters
  - ***Identify what wavelengths give most useful information for what planets***

Forward models & retrievals

- Use 1-D forward models:
  - Emission: Line+(2013a), Diamond-Lowe+(2014), Stevenson+(2014)
  - Transmission: Line+(2013b) Swain+(2014), Kreidberg+(2014, 2015)
- Transmission model has 11 free parameters:
  - T(SH), R(P=10b),hard clouds (Pc, σ_0, β), H_2O, CH_4, CO, CO_2, NH_3, N_2 absorbers, constant with altitude
- Emission model has 1D T-P profile & 10 free params
  - H_2O, CH_4, CO, CO_2, NH_3, 5 gray atm parameters for T-P (Line+ 2013a)
- CHIMERA Bayesian retrieval suite (Line+ 2013a,b)
  - Updated with emcee MCMC
  - Uniform & Jeffreys priors

Simulated Planet Signals (S_λ) & Noise (N_λ)

$$Tr_\lambda = \frac{S_\lambda(F_*) + Bkg - (S_\lambda(F(*+p)_{Tr}) + Bkg)}{S_\lambda(F_*) + Bkg - \langle Bkg \rangle}$$

and

$$Em_\lambda = \frac{S_\lambda(F(*+p)_{Em}) + Bkg - (S_\lambda(F_*) + Bkg)}{S_\lambda(F_*) + Bkg - \langle Bkg \rangle}$$

$$N_\lambda = \sqrt{S_\lambda + Bkg + N_{d,tot}^2}$$

$$N_{d,tot} = N_d \sqrt{n_{pix} n_{ints} R_{native}/R}$$

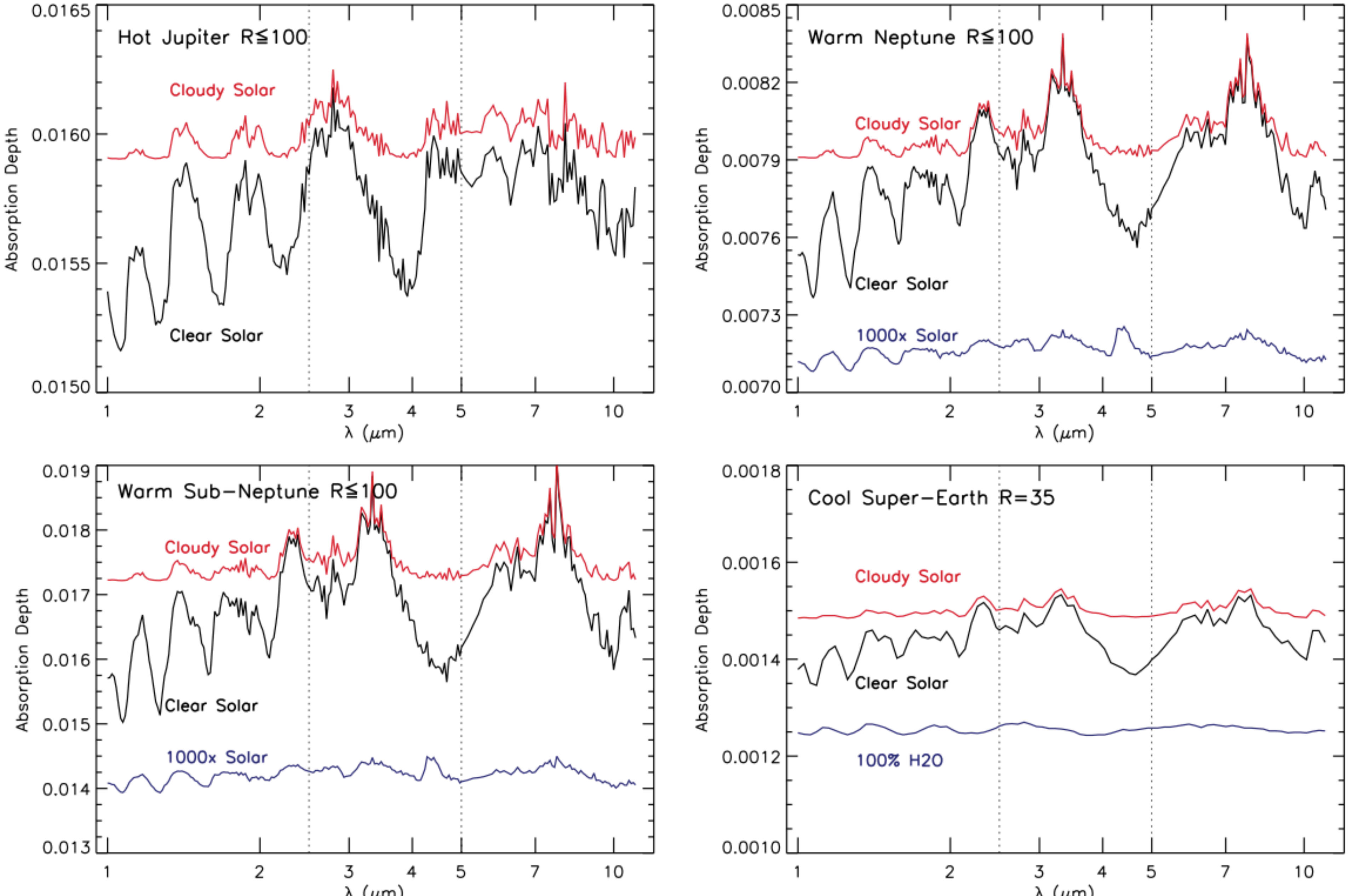
λ (μm)	Noise floor	
1.0 – 2.5	20 ppm	NIRISS
2.5 – 5.0	30 ppm	NIRCam
5.0 - 12	50 ppm	MIRI LRS

Selected Model Systems

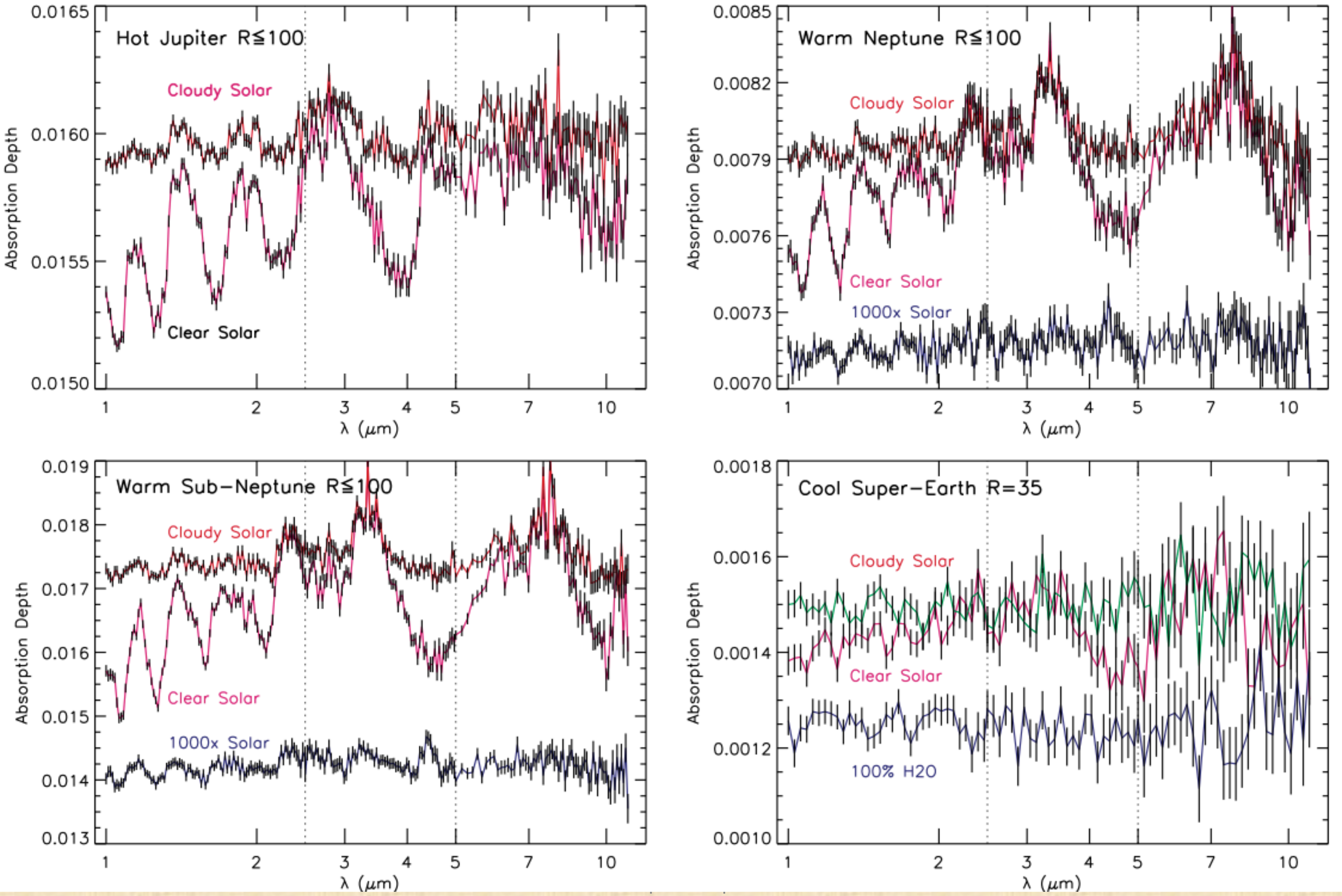
Planet Type	System Parameters	Composition	Clouds	Geometry
Hot Jupiter	HD 209458b	1x Solar	Clear	Trans, Emis
			1 mbar	Trans
Warm Neptune	GJ 436b	1x Solar	Clear	Trans, Emis
			1 mbar	Trans
		1000x Solar	Clear	Trans, Emis
Warm Sub-Neptune	GJ 1214b	1x Solar	Clear	Trans, Emis
			1 mbar	Trans
		1000x Solar	Clear	Trans, Emis
Cool Super-Earth	K2-3b	1x Solar	Clear	Trans, Emis
			1 mbar	Trans
		100% H_2O	Clear	Trans, Emis

Planet Type	System Parameters	T_* (K)	R_* ($R_\odot$)	K (mag)	T_{eq} (K)	M_p (M_{Jup})	R_p (R_{Jup})	H[a] (km)	T_{14} (s)
Hot Jupiter	HD 209458b	6065	1.155	6.3	1500	0.69	1.359	580	11,000
Warm Neptune	GJ 436b	3350	0.464	6.1	700	0.073	0.377	200	2740
Warm Sub-Neptune	GJ 1214b	3030	0.211	8.8	600	0.020	0.239	240	3160
Cool Super-Earth	K2-3b	3900	0.561	8.6	500	0.017	0.191	160	9190

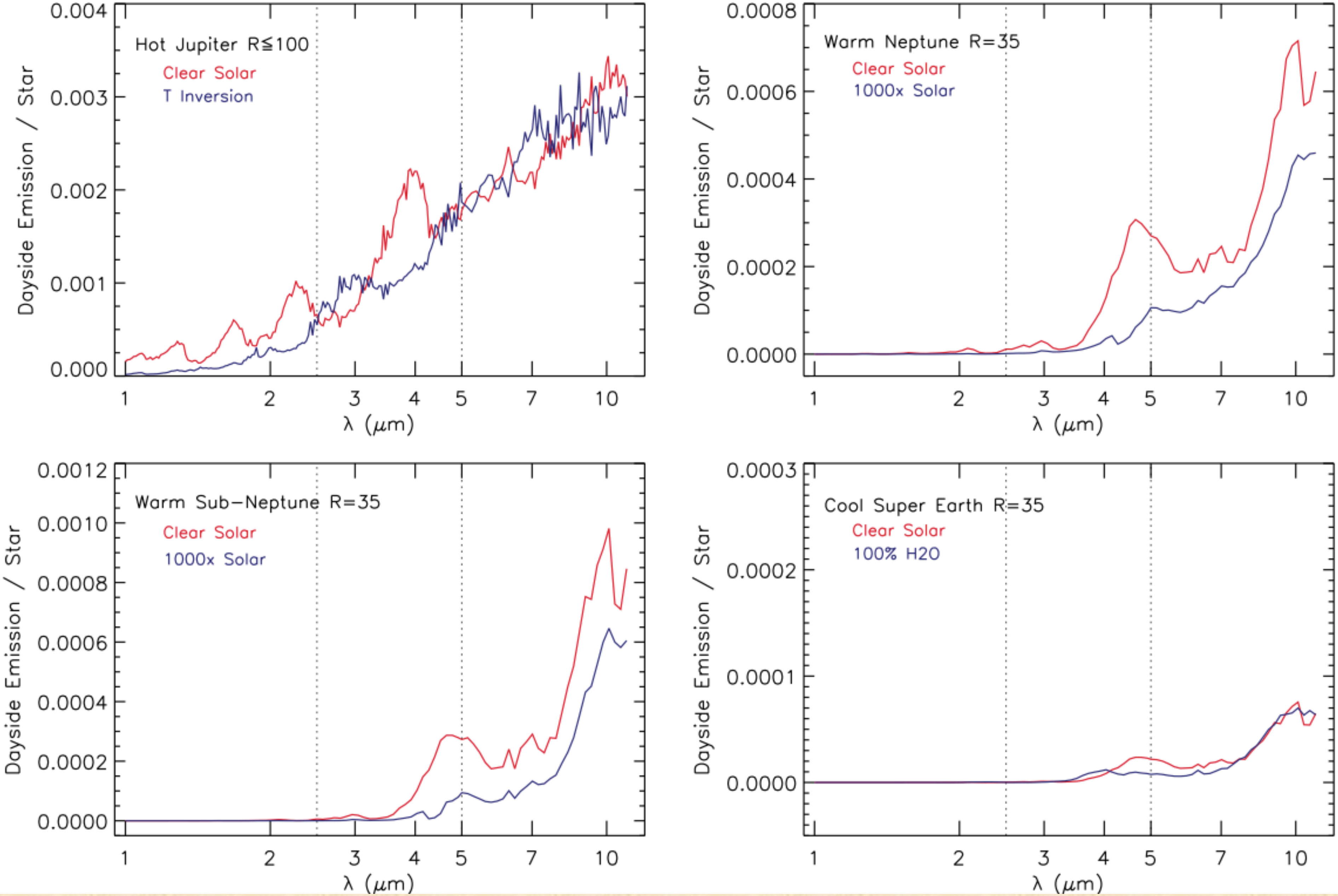
Model Transmission Spectra



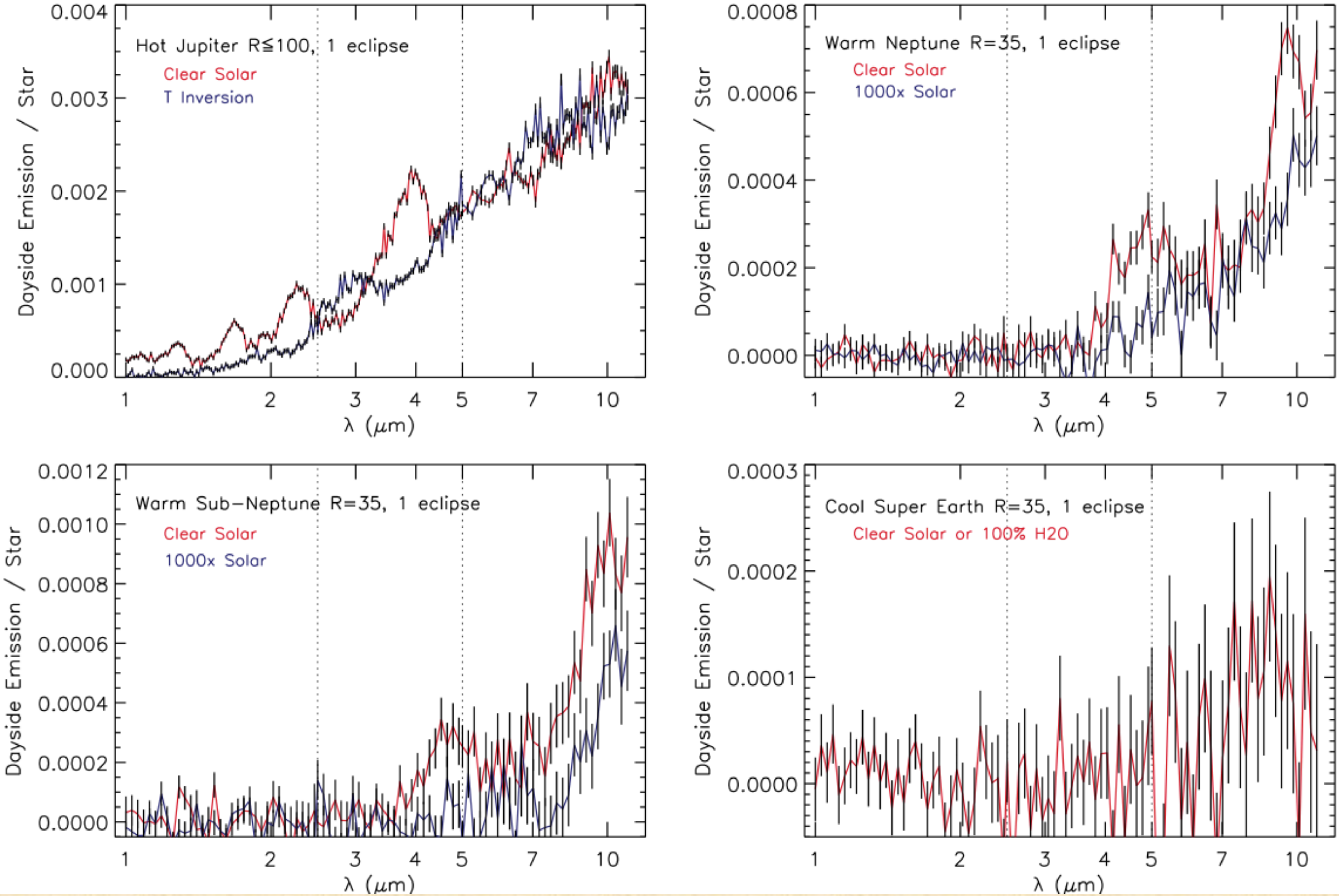
Simulated JWST Trans Spectra (1 transit)



Model Emission Spectra



Simulated JWST Emission Spectra (1 eclipse)



Retrieval Birds & Bees

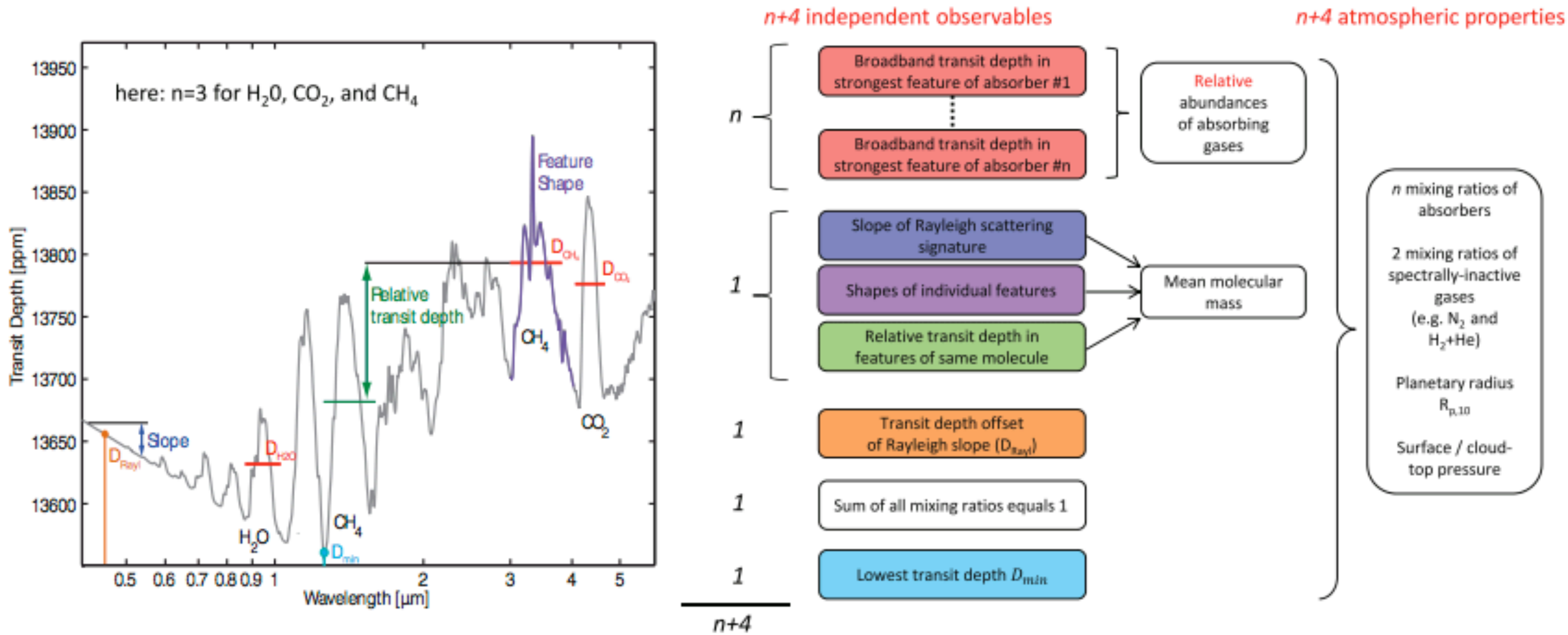
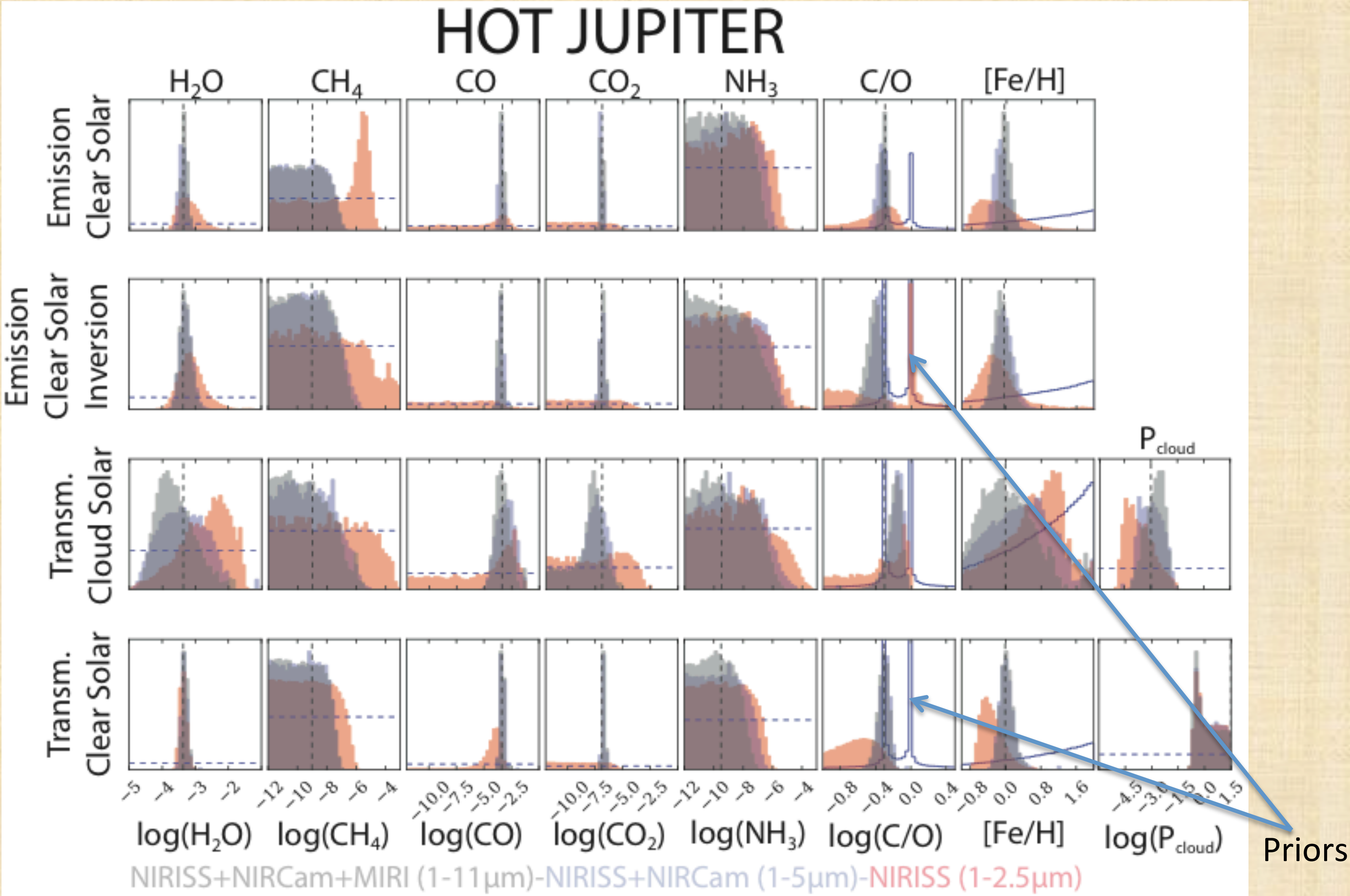


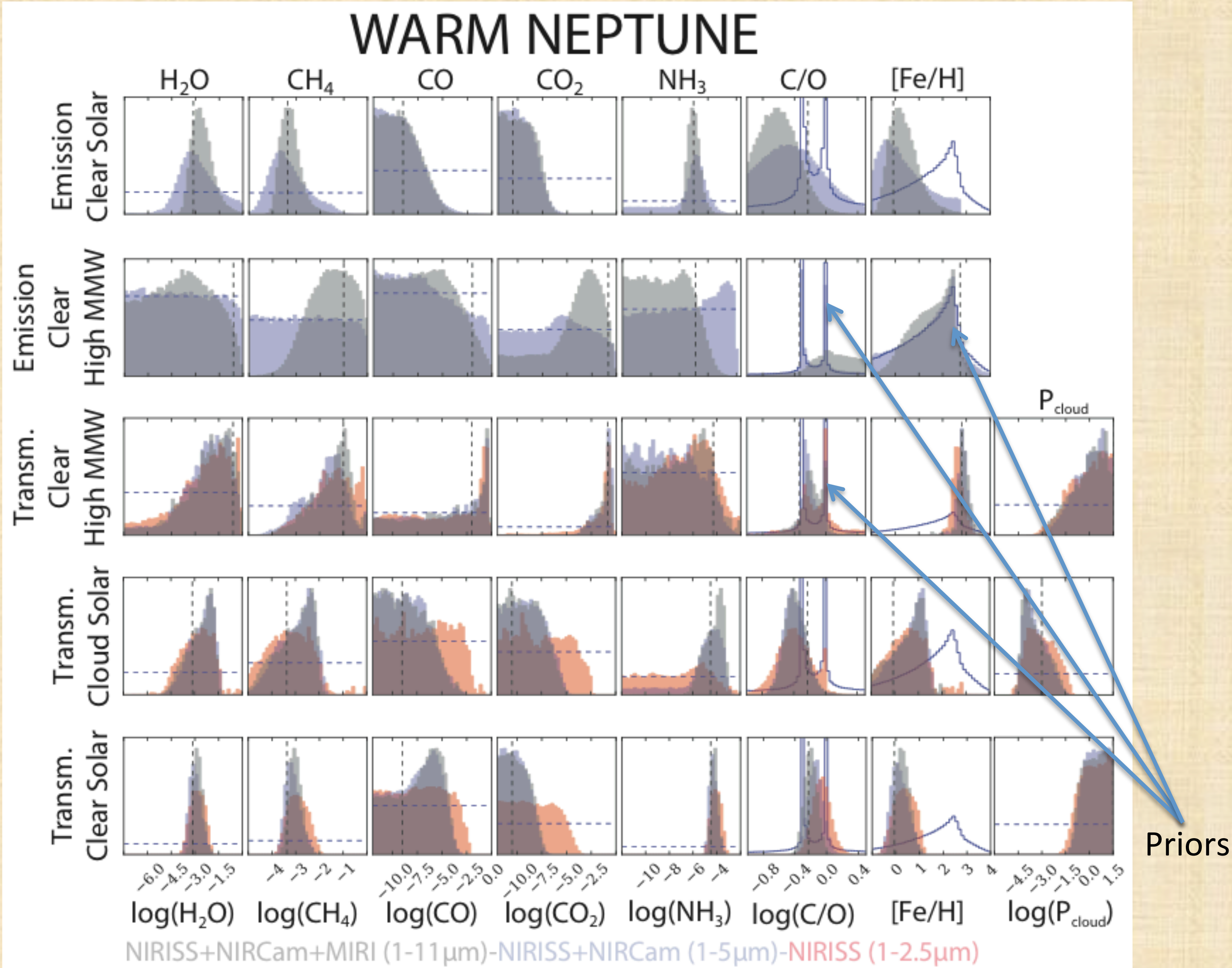
Figure 3. Unique constraints on the atmospheric properties based on observables in the transmission spectrum. The transmission spectrum of an atmosphere with n relevant absorbers contains $n+4$ independent pieces of information that constrain the n mixing ratios of these absorbers, up to two mixing ratios of the two spectrally inactive components H_2+He and N_2, the planetary radius at a reference pressure level, $R_{P,10}$, and the surface/cloud-top pressure. The left panel illustrates conceptually the individual observables in the transmission spectrum that carry the n+4 pieces of information for an example with $n = 3$ absorbers. For well-mixed atmospheres, the three observables "slope of the Rayleigh signature," "shapes of individual features," and "relative transit depths in features of same molecule" are redundant and provide only one independent piece of information. Note that to uniquely constrain *any* of the $n+4$ atmospheric properties on the far right, *all* $n+4$ pieces of information need to be available, unless additional assumptions are made.

Benneke & Seager (2012)

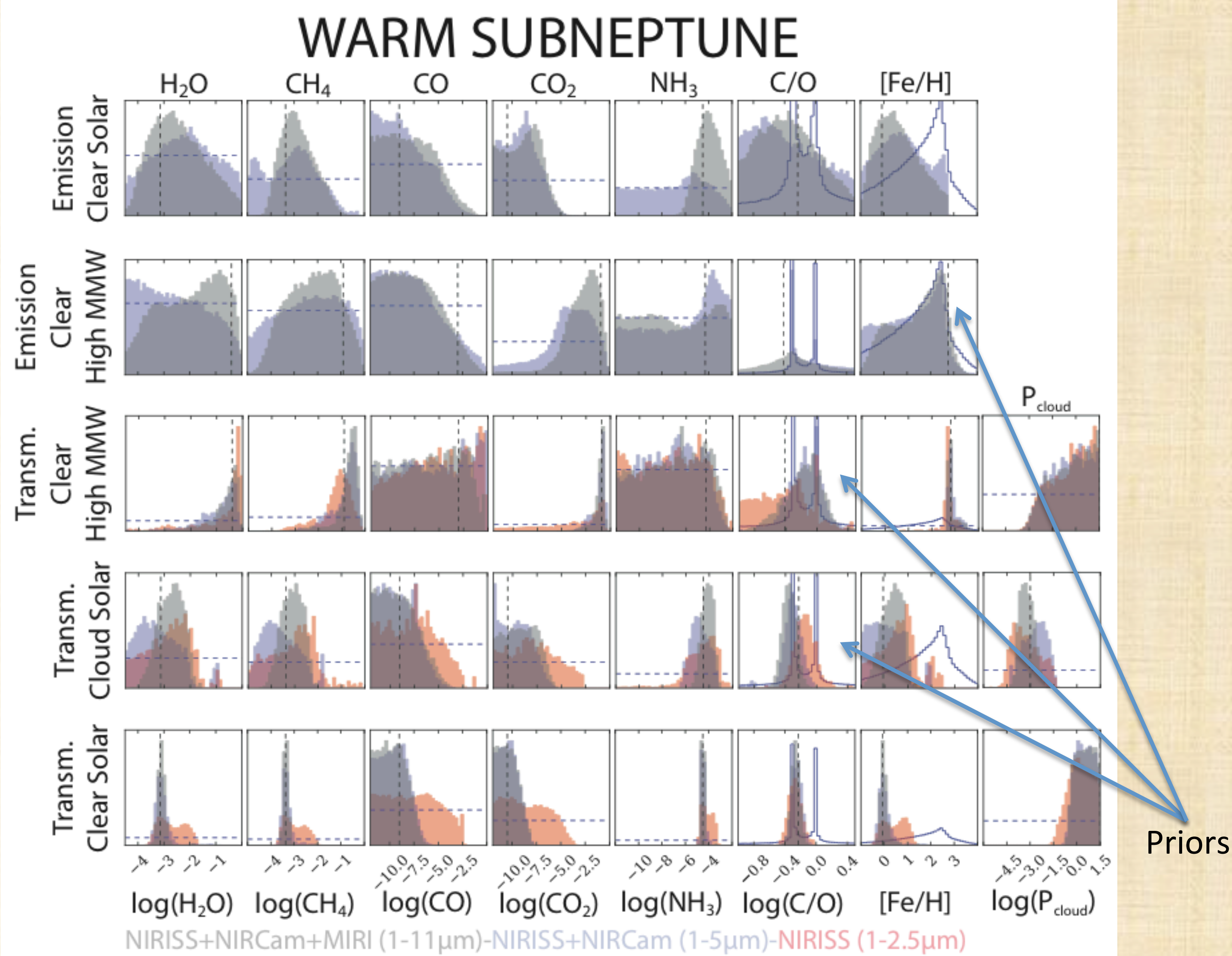
Retrieval: Hot Jupiter Gasses



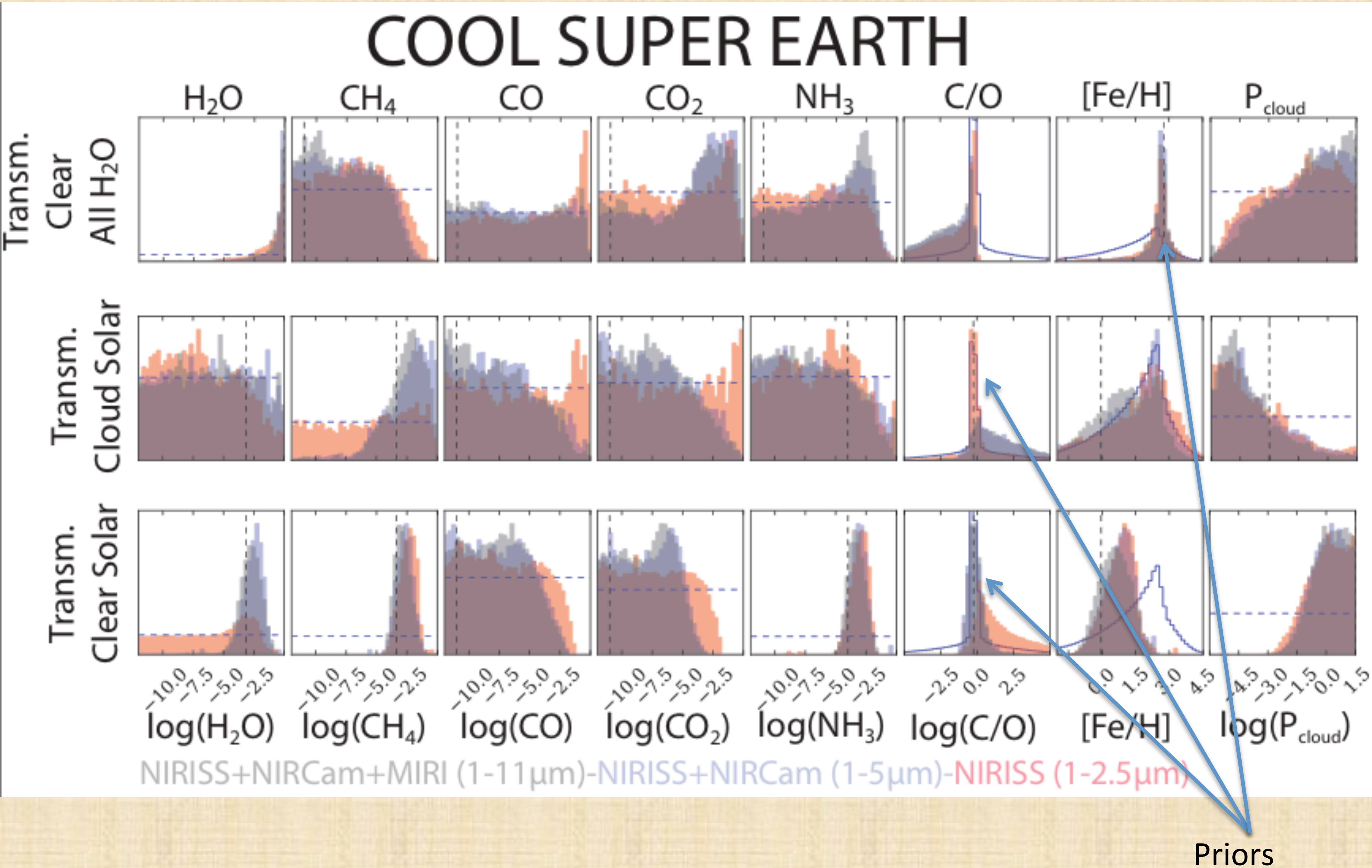
Retrieval: Warm Neptune Gasses



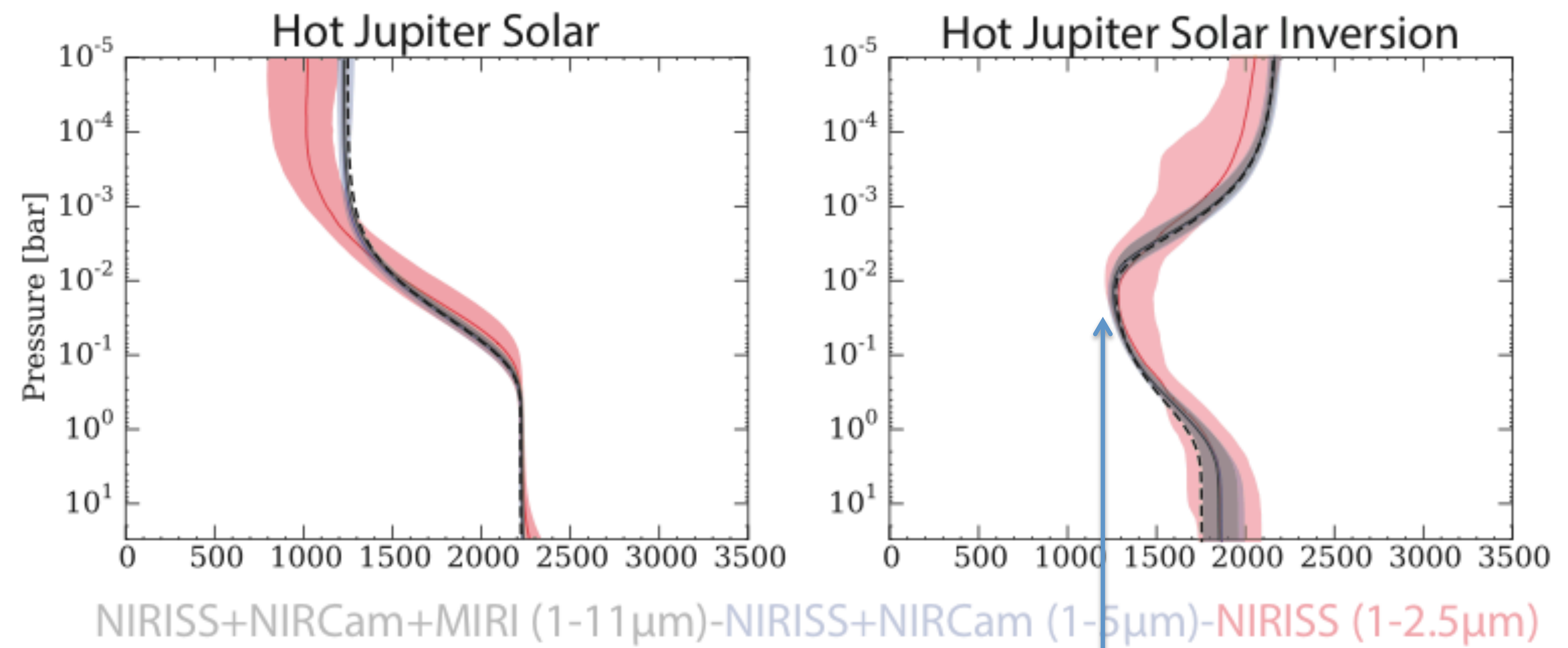
Retrieval: Warm Sub-Neptune Gasses



Retrieval: Cool Super-Earth Gasses

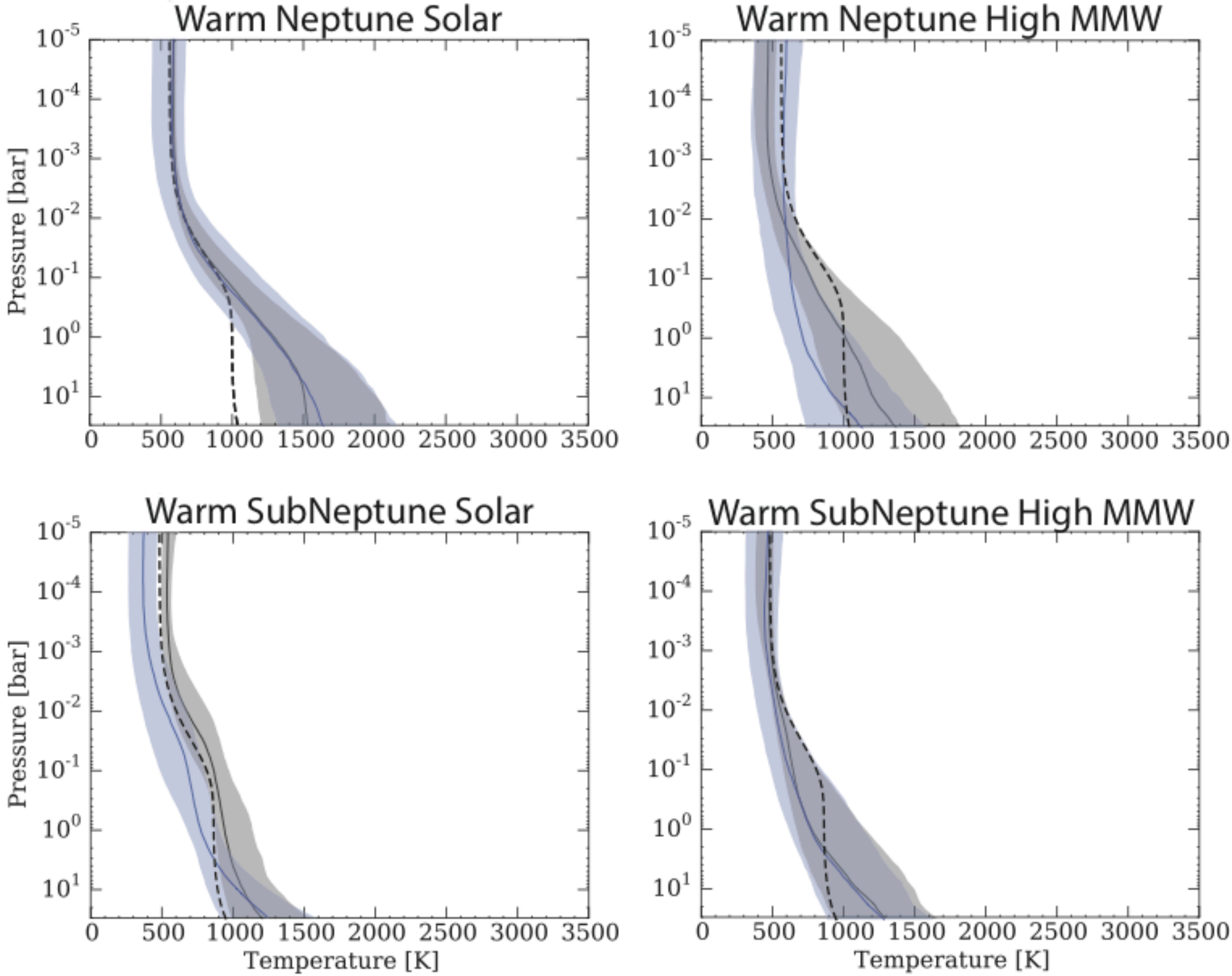


Emission retrievals: T-P Profiles



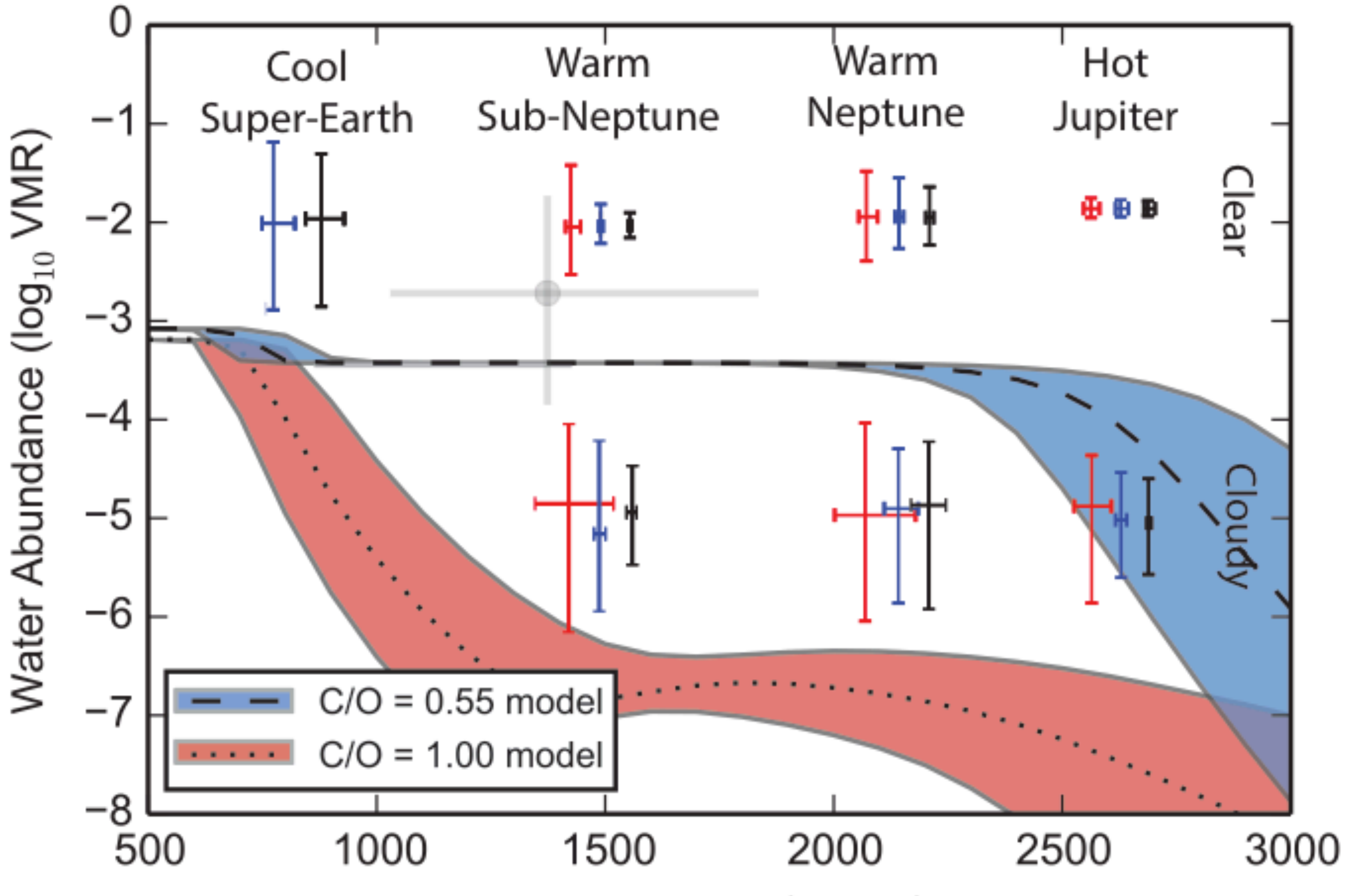
Dashed: True value
Solid line: Retrieved mean value
Shaded: 1 sigma

Detect inversion at 4 sigma
with NIRISS only (red)



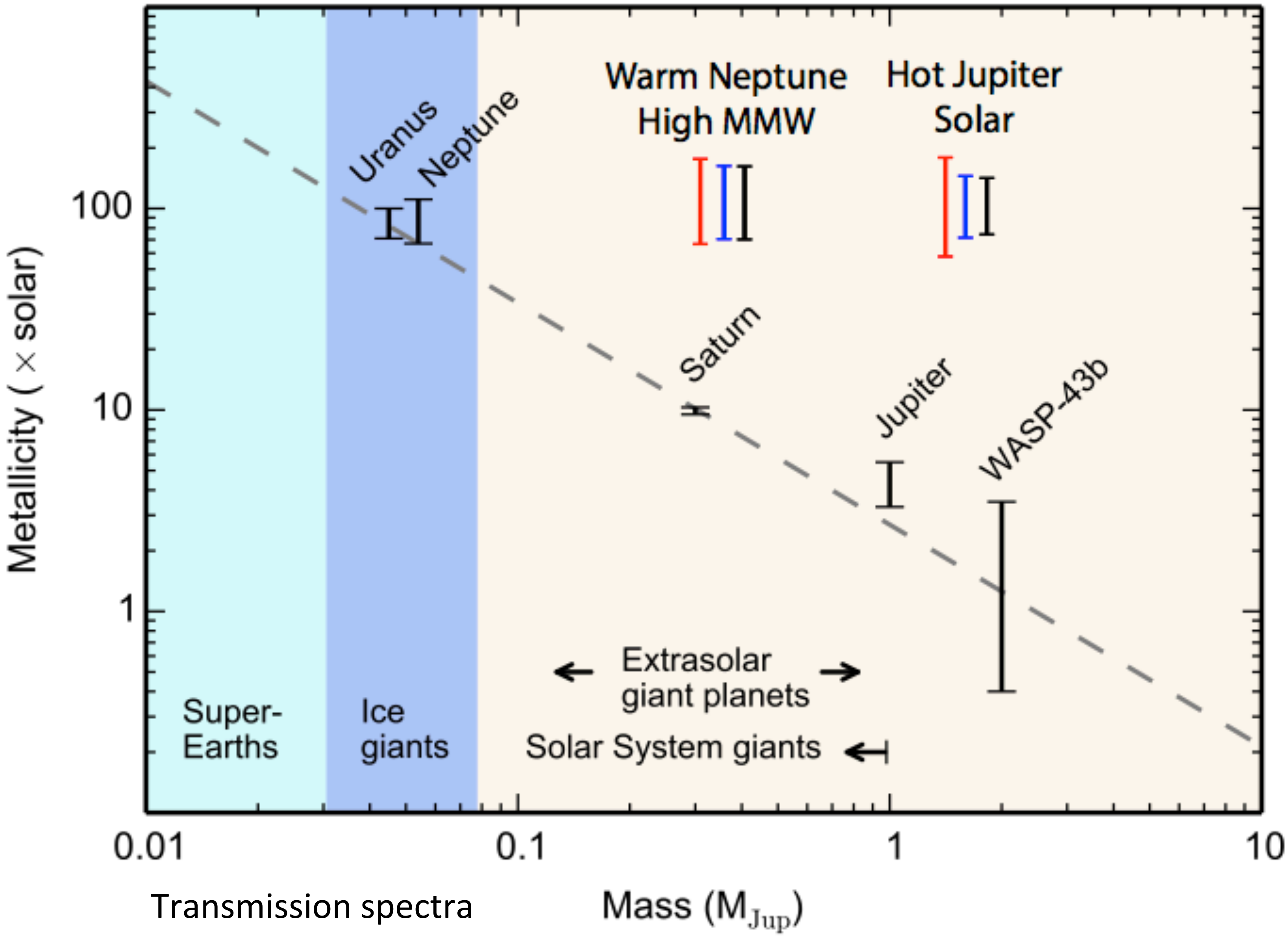
NIRISS+NIRCam+MIRI (1-11μm)-NIRISS+NIRCam (1-5μm)-NIRISS (1-2.5μm)

Constraining C/O from H_2O + T_{eq}



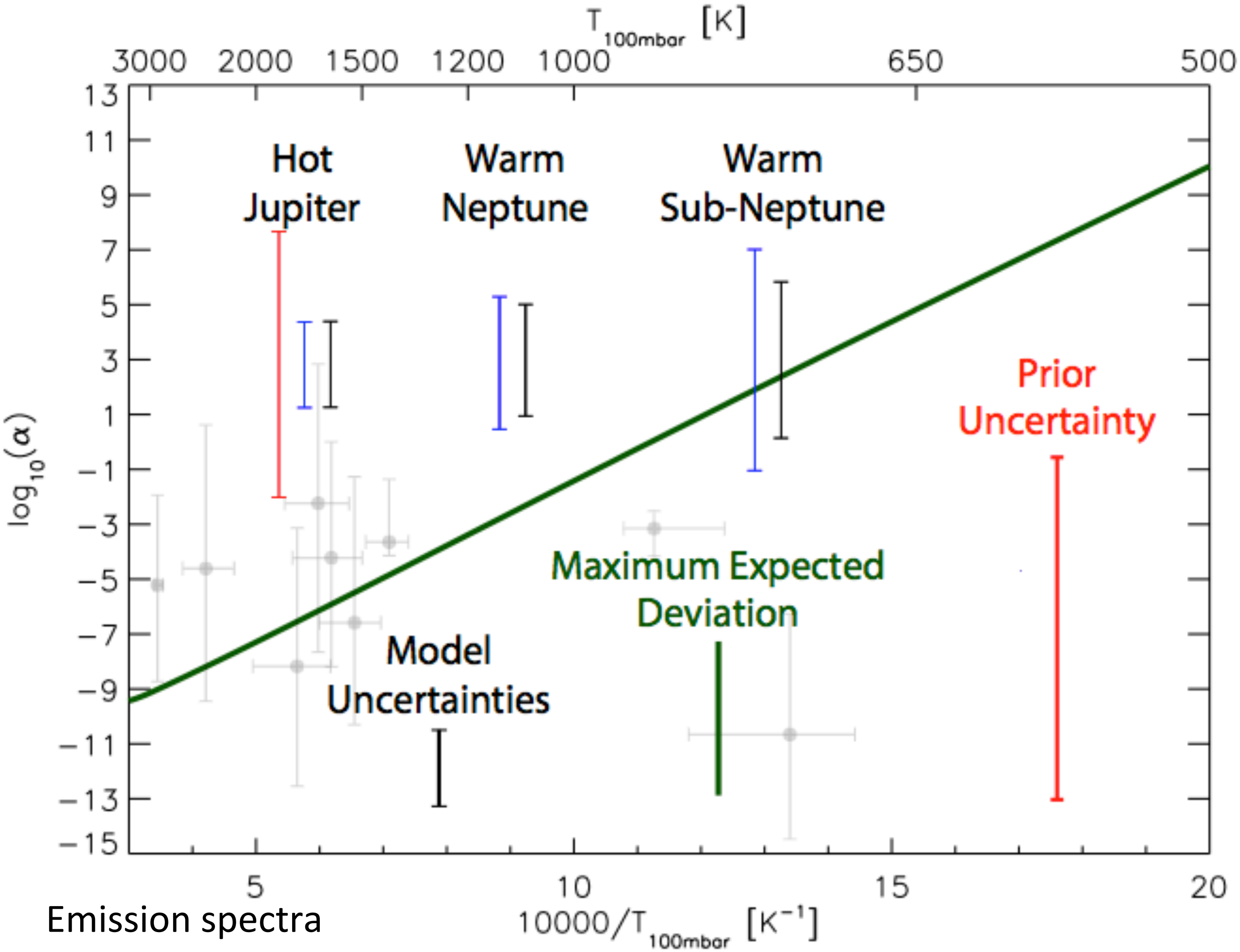
Transmission spectra

Mass - Metallicity



Transmission spectra

Dis-equilibrium Chemistry (v mixing)



Emission spectra

Summary / Conclusions (1)

- NIRISS (1 – 2.5 μm) transmission spectra alone often constrain mixing ratios of dominant molecules in clear solar atmosphere planets
  - C/O and [Fe/H] sometimes also constrained with only NIRISS
  - $\lambda \geq 5$ μm spectra needed in a number of cases
- Cloudy solar atmospheres are often constrained (~ 1 dex or better mixing ratios) with λ = 1 - 11 μm spectra
  - Transmission is better than emission for warm sub-Neptune
  - Hot Jupiter and warm Neptune do better with emission
    - Need sufficient F_p and high F_p/F_* for useful emission spectra
- High MMW atmospheres can be identified by high [Fe/H]
- C/O is constrained to 0.2 dex for hot Jupiters with λ = 1 – 5+ μm spectra. Also: C/O for hot planets with H2O + Teq
- σ[Fe/H] < 0.5 dex for warm, clear planets (λ = 1-5+ μm tr)

Summary / Conclusions (2)

- Non-equilibrium vertical mixing cannot be detected via mixing ratios
  - May be better to look for unexpected spectral features
- Observing 5 planets from Uranus to Jupiter mass should measure [Fe/H] vs. Log (M) slope to $1\sigma = 0.13$
  - $\lambda =$ 1-5+ μm transmission spectra
  - More than adequate (~5%) for detecting Solar System slope
- These results are for observations of single transits or eclipses. We will not know the actual JWST data quality – and how noise will decrease with co-adding – until after launch
- Many more retrieval issues to be explored (binning, Bayesian estimators, priors, 3D, parameterization), but will largely be driven by future data

The End